CRITICAL BEHAVIOUR IN PERIPHERAL Au + Au COLLISIONS AT 35 MeV/u

M. Bruno[1], P. F. Mastinu[1,3], M. Belkacem[1,9], M. D'Agostino[1], P. M. Milazzo[1,2], G. Vannini[2], D. R. Bowman[7], J. D. Dinius[6], A. Ferrero[4,8], M. L. Fiandri[1], C. K. Gelbke[6], T. Glasmacher[6], F. Gramegna[5], D. O. Handzy[6], D. Horn[7], W. C. Hsi[6], M. Huang[6], I. Iori[4], G. J. Kunde[6], M. A. Lisa[6], W. G. Lynch[6], G. V. Margagliotti[2], C. P. Montoya[6], A. Moroni[4], G. F. Peaslee[6], R. Rui[2], C. Schwarz[6], M. B. Tsang[6], C. Williams[6], V. Latora[9] and A. Bonasera[9]

[1] *Dipartimento di Fisica and INFN, Bologna, Italy*
[2] *Dipartimento di Fisica and INFN, Trieste, Italy*
[3] *Dipartimento di Fisica, Padova, Italy*
[4] *Dipartimento di Fisica and INFN, Milano, Italy*
[5] *INFN, Laboratori Nazionali di Legnaro, Italy*
[6] *NSCL, Michigan State University, USA*
[7] *Chalk River Laboratories, Chalk River, Canada*
[8] *On leave from CNEA, Buenos Aires, Argentina*
[9] *INFN, laboratorio Nazionale del Sud, Catania, Italy*

The signals theoretically predicted for the occurrence of a critical behavior (conditional moments of charge distributions, Campi scatter plot, fluctuations of the size of the largest fragment, power law in the charge distribution, intermittency) have been found for peripheral events in the reaction Au+Au at 35 MeV/u. The same signals have been studied with a dynamical model which foresees phase transition, like the Classical Molecular Dynamics.

1 Introduction

The liquid-gas phase transition in nuclear systems has been recently theoretically and experimentally investigated [1,2,3]. In this contribution we report on the search for critical behavior signals in the experimental data of the Au + Au reaction at 35 MeV/u. The experiment was performed at the National Superconducting Cyclotron Laboratory of the Michigan State University taking advantage of the coupling of the Multics [4] and the Miniball [5] apparatus. The analysis has been restricted to events corresponding to peripheral and semi-peripheral reactions, selected imposing that the component of the velocity of the largest fragment along the beam direction was greater than 75% of the beam velocity and that the total detected charge was between 70 and 90. Most of these events come from the disassembly of the quasi-projectile, since the detection of the quasi-target is suppressed due to the thresholds of the detectors.

Comparisons with the results of calculations in the framework of Classical

Figure 1: Campi scatter plot, $ln(Z_{max})$ versus $ln(M_2)$. The three different regions are discussed in the text. Fission events are to the right of region 2.

Molecular Dynamics model (CMD) [3,6] are also presented.

2 Experimental results

The events selected with the previously mentioned criterion have been plotted (see Fig. 1) as $ln(Z^j_{max})$ vs. $ln(M^j_2)$ (Campi scatter plot [7]), where Z^j_{max} is the charge of the heaviest fragment and M^j_2 is the second conditional moment of the charge distribution detected in the j-th event, $M_2^{(j)} = \sum_Z Z^2 n_j(Z)/Z_0$ where $n_j(Z)$ is the number of fragments of charge Z detected in the j-th event, Z_0 is the total charge and the summation is over all fragments but the heaviest detected one.

The data in Fig. 1 are distributed along two branches as predicted by percolation calculation for undercritical and overcritical events. To have a deeper insight in the behavior of events falling in different regions of the Campi-plot, we selected three different cuts in the upper branch (cut 1), in the lower one (cut 3) and in the intersection region (cut 2). The charged particle multiplicity distributions observed for these three cuts show that cuts 1 and 3 select low and high multiplicity events with a narrow range, whereas for the cut 2 a wide range of charged particle multiplicities has been observed [8], possibly related to the occurrence of large fluctuations as expected at the critical point. Even when the width of region 2 is reduced, the multiplicity distribution remains quite broad.

The fragment charge distribution corresponding to cut 1 contains light fragments and heavy residues, thus exhibiting a "U"-shaped distribution. For cut 3 it is rapidly decreasing. The results obtained for cut 1 and cut 3 are similar to the predictions of percolation calculations in the sub-critical region [9], with the probability p higher than the critical one (p_C), and in the overcritical

Figure 2: Relative variance γ_2 (left panel) and normalized variance of the charge of the largest fragment σ_{NV} (right panel) as a function of charged particle multiplicity

region ($\mathrm{p}<\mathrm{p}_C$), respectively. Similar trends have been observed also for the predictions from dynamical[10] and statistical calculations[11] for subcritical ($\mathrm{T}<\mathrm{T}_C$) and overcritical events ($\mathrm{T}>\mathrm{T}_C$), respectively. The fragment charge distribution for cut 2 shows a power-law distribution, $P(Z) \propto Z^{-\tau}$, with $\tau \approx 2.2$. For macroscopic systems exhibiting a liquid-gas phase transition, such a power-law distribution is predicted to occur near the critical point[12].

An analysis in term of Scaled Factorial Moments (SFM) has been performed. The SFM are defined[13] as

$$F_i(\delta s) = \frac{\sum_{k=1}^{Z_{tot}/\delta s} < n_k \cdot (n_k - 1) \cdot ... \cdot (n_k - i + 1) >}{\sum_{k=1}^{Z_{tot}/\delta s} < n_k >^i} \tag{1}$$

where $Z_{tot} = 158$, and i is the order of the moment. The total interval $[1, Z_{tot}]$ is divided into $M = Z_{tot}/\delta s$ bins of size δs, n_k is the number of particles in the k-th bin for an event, and the brackets $<>$ denote the average over many events. The values $ln(F_i)$ for $i = 2$, ..., 5 are always negative (i.e. the variances are smaller than for a Poissonian distribution) and almost independent on δs for cut 3. For cut 2, $ln(F_i)$ are positive and almost linearly increasing as a function of $-ln(\delta s)$ (i.e. $F_i \propto \delta s^{-\lambda_i}$), and this, as pointed out by several theoretical studies[3,13], indicates an intermittent pattern of fluctuations[11,14,13]. Region 1, corresponding to evaporation, gives zero slope. Increasing or reducing the sizes of the three cuts does not change significantly these results.

Further signals which could reveal the presence of a critical behaviour have been investigated. The second moment M_2 shows a peak versus the multiplicity of charged particles in the region of $N_c \simeq 20$. A similar value is obtained by the EOS Collaboration[2]. Also the relative variance γ_2, defined as[7,13]: $\gamma_2 = \frac{M_2 M_0}{M_1^2}$

Figure 3: Campi scatter plot (left panel) and normalized variance of the charge of the largest fragment σ_{NV} vs. charged particle multiplicity (right panel) for the events predicted by CMD calculations, filtered through the experimental acceptance, with the same conditions applied to the experimental data to select peripheral events (see text).

shows a peak for $N_c \approx 18 - 22$ (see Fig. 2), consistent with that observed for M_2; this means that around $N_c \approx 20$ the fluctuations in the fragment size distributions are large, as it should be near the critical point [7].

A further signal for criticality, recently proposed [15], is the normalized variance of the charge of the largest fragment σ_{NV}. This quantity, defined by: $\sigma_{NV} = \frac{\sigma^2_{Z_{max}}}{<Z_{max}>}$ where $\sigma^2_{Z_{max}} =< Z^2_{max} > - < Z_{max} >^2$ shows a peak at the critical point, where charge distributions are expected to show the largest fluctuations. The right side of Fig. 2 shows the σ_{NV} versus charged particle multiplicity for the experimental data. A clear peak is present for multiplicities $N_c \approx 15 \div 20$.

The analysis of the experimental data suggests that different regions of the nuclear phase diagram can be probed at one incident beam energy by selecting different events [16]. All the signals so far proposed to characterize a critical behavior have been found. We must however caution that the effects of finite experimental acceptance and the mixing of possible contributions from the decay of projectile-like fragments and the neck-region are not yet sufficiently well understood to allow an unambiguous conclusion.

3 Model calculations

In the framework of the CMD model, calculations have been performed for impact parameter ranging from 1 to 13 *fm*. The Campi scatter-plot for the calculated events is very similar to the experimental one. Also M_2, γ_2 and σ_{NV} show a peak for b $\approx$ 10 fm and for $N_c \approx 20 - 25$. An analysis of the events in a region corresponding to the region 2 of the experimental data show a similar

Figure 4: Normalized variance of the charge of the largest fragment σ_{NV} vs. charged particle multiplicity for the events predicted by simulations as described in the text.

behavior with a clear signal of intermittency.

To account for the angular acceptance and detection thresholds of the apparatus, the predictions have been suitably filtered; the same type of selection used to characterize the experimental events of peripheral or semi-peripheral reactions has then been applied. All the signals are clearly visible; in Fig. 3 the Campi-plot and the σ_{NV} with a peak in the region of b $\approx$ 10 fm and for $N_c \approx 15$ are shown. The same kind of analysis performed for experimental data gives the same results both for the charge distribution and for the SFM.

4 Discussion and Conclusions

In addition to the calculations based on percolation and on statistical and dynamical models, a series of simulations have been performed, mainly starting from a given mass or charge distribution: considering the charge and mass conservation [17] or starting from a simple power law mass distribution [18], several signals like the Campi plot, M_2, γ_2 and the intermittency have been observed. Recently a simulation based on an exponential charge distribution [19] with a binomial coefficient shows several of the signals experimentally obtained. In particular, peaks have been obtained for M_2 and γ_2, but for instance no peak is present for σ_{NV}, as shown in Fig. 4. The simple presence of peaks, however, could be not relevant and it could be important to investigate position, height and widths of the peaks.

On the other side, the signals proposed so far might be not sufficient to characterize a critical behavior or the data extracted by the simulation could be "somehow" connected to the experimental data which contain the criticality, through some constraint like the charged particle multiplicity distribution.

In conclusion we have analyzed the peripheral events of the reaction Au + Au at 35 MeV/u and we have found all the signals proposed to evidence out a critical behavior; these findings have been confirmed by predictions based on a dynamical model like CMD. Further work is needed before suggesting any definite conclusion.

References

1. see e.g. H. R. Jaqaman, Gabor Papp and D. H. E. Gross, *Nucl. Phys.* A **514**, 327 (1990); J. Pochodzalla *et al.*, *Phys. Rev. Lett.* **75**, 1040 (1995).
2. J. B. Elliot *et al.*, *Phys. Rev.* C **49**, 3185 (1994); M. L. Gilkes *et al.*, *Phys. Rev. Lett.* **73**, 1590 (1994).
3. M. Belkacem, V. Latora and A. Bonasera, *Phys. Rev.* C **52**, 271 (1995).
4. I. Iori *et al*, *Nucl. Instrum. Methods* A **325**, 458 (1993).
5. R. T. DeSouza *et al*, *Nucl. Instrum. Methods* A **49**, 109 (1990);
6. R. J. Lenk, T. J. Schlagel and V. R. Pandharipande, *Phys. Rev.* C **42**, 372 (1990).
7. X. Campi, *J. of Phys.* A **19**, L917 (1986); *J. de Phys.* **50**, 183 (1989), X. Campi and H. Krivine, *Nucl. Phys.* A **589**, 505 (1995).
8. P. F. Mastinu *et al.* *nucl-ex/9604001*, XXXIV Int. Winter Meeting on Nucl. Phys, Bormio, 1996, Ricerca Scientifica, Ed. Perm, Vol. 102,page 110.
9. W. Bauer *et al*, *Phys. Lett.* B **150**, 53 (1985); *Nucl. Phys.* A **452**, 699 (1986); *Phys. Rev.* C **38**, 1297 (1988).
10. M. Belkacem *et al.* XXXIV Int. Winter Meeting on Nucl. Phys, Bormio, 1996, Ricerca Scientifica, Ed. Perm, Vol. 102,page 96.
11. H. R. Jaqaman and D. H. E. Gross, *Nucl. Phys.* A **524**, 321 (1991); D. H. E. Gross, *et al.* *Phys. Rev. Lett.* **68**, 146 (1992).
12. M. E. Fisher, *Rep. Prog. Phys.* **30**, 615 (1967); *Physics* **3**, 255 (1967).
13. M. Ploszajczak and A. Tucholski, *Phys. Rev. Lett.* **65**, 1539 (1990); *Nucl. Phys.* A **523**, 651 (1991).
14. A. Bialas and R. Peschanski, *Nucl. Phys.* B **273**, 703 (1986); *Nucl. Phys.* B **308**, 857 (1988).
15. J. B. Elliot, Phase Transitions in Small Systems, GSI, Darmstadt, December 1995.
16. J. Pochodzalla (this conference)
17. Sa Ben-Hao *et al.* *J. o Phys.* G: Nucl. Part. Phys. **21**, 241 (1995).
18. B. Elattari, J. Richert and P. Wagner *Nucl. Phys.* A **560**, 603 (1993)
19. L. Phair (*private communication*).